Industrial Revolution and Scientific and Technological Progress

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Concept and Spread of the Industrial Revolution

The industrial revolution is traditionally considered the most important break in the history of mankind since the Neolithic Period: 'Between 1780 and 1850, in less than three generations, a far-reaching revolution, without precedent in the history of Mankind, changed the face of England. From then on, the world was no longer the same. Historians have often used and abused the word revolution to mean a radical change, but no revolution has been as dramatically revolutionary as the Industrial Revolution - except perhaps the Neolithic Revolution' (Cipolla 1975, p. 7). The industrial revolution marks the beginning of a self-sustained process towards modern economic growth with increasing income per capita (Kuznets 1966). For a long time the first industrial nation (Mathias 1969), namely Britain, was regarded as the blue print or model for all the industrial revolutions achieved in the follower countries.[1] During the 18th century a cluster of innovations had led to the rise of industry and the emergence of the factory system in Britain. According to Landes, these innovations could be subsumed under three principles: 'the substitution of machines - rapid, regular, precise, tireless - for human skill and effort; the substitution of inanimate for animate sources of power, in particular, the introduction of engines for converting heat into work, thereby opening to man a new and almost unlimited supply of energy; the use of new and far more abundant materials, in particular, the substitution of mineral for vegetable or animal substance' (Landes 1969, p. 41). The classic, traditional view of the industrial revolution in general focuses on two related aspects: an unprecedented change of techniques accompanied by a rising income per capita without any upper limit.

This traditional view of the industrialisation has been questioned in at least three respects: When Cameron labels the term of Industrial Revolution a misnomer he first of all doubts its *revolutionary* character (Cameron 1989, pp. 163-165). Calculations of aggregate growth rates of income indeed do not show a rapid increase within a short period of, say, 30 years for Britain

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1 'She [Britain] was, in short, the very model of industrial excellence and achievement ....' (Landes 1969, p. 124).

(Crafts 1994), and hence indicate no take-off in a Rostowian[2] sense. Furthermore a continuous flow of small improvements attained by tinkering on the job (von Tunzelmann 1981) proved at least equally important as the spectacular Schumpeterian[3] 'basic' innovations.[4] Secondly, there were different paths leading to modern economic growth (O'Brien/Keyder 1978). There is moreover convincing evidence that the British growth path was the exception rather than the norm (Crafts 1984). Thirdly, the uniqueness of the growth process ushered in with the industrial revolution has raised scepticism. In the course of the economic history of western Europe one can at least identify two long waves of growth (11-13th centuries, 15-16th centuries) before the industrial revolution. Those phases of expansion, however, ended up in the Malthusian[5] trap, with population growth reaching the ceiling built in by the limits to growth. There are apprehensions that the same might happen with modern economic growth: The Neo-Malthusian Report of the Club of Rome (1972) generalised Malthus' view for the entire earth and predicted a global environmental catastrophe, if population growth and the actual use of resources for production and consumption did not change radically (Meadows et al. 1972).

Notwithstanding these objections to the traditional view of industrialisation it seems rather clear that on a world-wide scale there was a revolutionary break with the past indeed. As this break did not force up the rate of economic growth all at once 'it is appropriate to think about the Industrial Revolution primarily in terms of accelerating and unprecedented technological

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2 In Rostow's (US American) stage theory, every country will pass through five different stages of economic growth: 'The traditional society. The preconditions for take-off. The take-off. The drive to maturity. The age of high mass-consumption' (Rostow 1960). Crucial is the 'take-off'. This industrial revolution marks the beginning of sustained growth of per capita income. The transition of a revolutionary nature is characterised by its short duration (around thirty years), by a substantial increase of the investment ratio (from below five to above 10 percent of national income) and by the first appearance of leading sectors, which drive economic growth through successive major technical innovations. This theory of unbalanced growth was a model for development policies proposed and pursued by the United States of America in the 1960s and it was of great influence in New Industrialising Countries like South-Korea. Furthermore Rostow's view provoked scholarly controversies in economic history: e.g. the contribution of the leading sector *railway* to economic growth during the 19th century (Fogel 1964; O'Brien 1983).

3 The term 'Innovation' was introduced by the Austrian/German/US American economist Schumpeter in his doctoral dissertation in 1911. 'Die Theorie der wirtschaftlichen Entwicklung' (Translation into English 1934, Theory of Economic Development) tries to explain the driving force behind capitalistic economic growth. The 'Pionierunternehmer' (pioneerentrepreneur) introduces inventions, or new combinations of the factors of production, into the economic system, thus accomplishing innovations. Schumpeter discriminated among five different types of innovations:

1. New products
2. New production processes
3. New sales markets
4. New sources for raw materials and intermediate products
5. New organisations or new institutions

The term 'basic' innovation ('Basisinnovation'), however, was coined by Neo-Schumpeterians, e.g. Mensch (1979).

4 'The Industrial Revolution was not the Age of Cotton or of Railways or even of Steam entirely; it was an age of improvement' (McCloskey 1981, p. 118).

5 The Briton Thomas Robert Malthus (1766-1834) put forward the tension between population growth and the potential growth of food supply. Populations, nations and its peoples are caught in a Malthusian trap (with famines, widespread diseases and hence high death rates) when population growth has outstripped the available means of subsistence. See Malthus: "An Essay on the Principle of Population", 1798.

change' (Mokyr 1990, p. 82). Economic growth has to be seen as outcome of a broader process which includes also productivity gains and the growth of output in agriculture and the service sector. A successful industrialisation, however, was sufficient to economic growth. And since the so-called industrial revolution modern economic growth has been a world-wide phenomenon after all. According to the calculations of world's economic growth by the British and Dutch scholar Angus Maddison, this break with the past becomes palpable: between 1500 and 1820 world population grew annually by 0.29%, gross domestic product (GDP) per capita by 0.04%, and world's GDP by 0.33%. Between 1820 and 1992, however, the same categories witnessed a growth rate of 0.95%, 1.21% and 2.17% respectively (Maddison 1985, p. 20). 'Growth performance since 1820 has been dramatically superior to that in earlier history. [....] Before our present 'capitalistic' epoch, economies were predominantly agrarian, and economic advance was largely extensive. In response to demographic pressure, economic activity was successful over the long term in sustaining living standards, but technology was virtually stagnant and evidence of advances in economic well-being is very meagre' (Maddison 1995, p. 19). Taking separate nations with their performance individually (see Table 1) belittles this fundamental achievement of modern economic growth in the history of mankind. The desirable global approach should not blur the different paths the specific nations or world regions have taken since the industrial revolution.

In Table 1 for selected countries in certain world regions the level of Gross Domestic Product (GDP) per Capita and the size of the population is given for the benchmark years 1820, 1913 and 1992. The empirical basis and the underlying methodology of the GDP-figures in 1990 Dollars may be questioned for those early years of 1820 and 1913. Given our present knowledge about the 19th century they provide a rough but correct picture of relative performance levels among nations and world regions, though. Since the GDP per Capita is still the best single indicator of welfare levels and the standard of living the relative performance among nations also reveals information about the average well-being of people in different regions of the world. Leading performers have been western European countries and offshoots of European settlements in North-America and the Pacific. The major exception have been Japan from the late 19th century onwards and recently some newly industrialising countries in South-East-Asia. The other big Asian nations with their huge population have still acquired no more than moderate income levels. Latin American countries did not perform badly during the 19th century and the early decades of the 20th century. From then on, however, they have fallen far behind the leading group in terms of economic growth. Southern European countries have caught up recently whereas eastern European nations still have to suffer under the heritage of mismanaged planned economies of the defaulted communist regime. Taken as a whole Africa has remained the poorest continent, with substantial variations among different countries, though. It seems pretty clear that those world regions or countries which underwent an industrial revolution already in the 19th century have had the best performance in modern economic growth until today.

Table 1 *GDP per Capita and Population of Selected Countries, 1820, 1913, 1992 (in 1990 international dollars and thousands)*

Country	1820		1913		1992	
	GDP	Population	GDP	Population	GDP	Population
Africa						
Egypt	-	-	508	12.144	1.927	54.679
Ghana	-	-	648	2.043	1.007	15.800
South Africa	-	-	1.451	6.153	3.451	37.600
Asia						
China	523	381.000	688	437.140	3.098	1.167.000
India	531	175.349	663	251.906	1.348	881.200
Indonesia	614	17.927	917	49.934	2.749	185.900
Japan	704	31.000	1.334	51.672	19.425	124.336
Latin America						
Argentinia	-	534	3.797	7.653	7.616	33.003
Brasil	670	4.507	839	23.660	4.637	156.012
Mexico	760	6.587	1.467	14.970	5.112	89.520
Eastern Europe						
Czechoslovakia	849	7.190	2.096	13.245	6.845	15.615
Hungary	-	4.571	2.098	7.840	5.638	10.313
USSR	751	50.398	1.488	156.192	4.671	292.375
Southern Europe						
Greece	-	-	1.621	5.425	10.314	10.300
Spain	1.063	12.203	2.255	20.263	12.498	39.085
Western Europe						
France	1.218	31.250	3.452	41.463	17.959	57.372
Germany[a]	1.112	14.747	3.833	37.843	19.351	64.846
Italy	1.092	20.176	2.507	37.248	16.229	57.900
Netherlands	1.561	2.355	3.950	6.164	16.898	15.178
UK	1.756	19.832	5.032	42.622	15.738	57.848
North America/Australia						
USA	1.287	9.656	5.307	97.606	21.558	255.610
Canada	893	741	4.213	7.852	18.159	28.436
Australia	1.528	33	5.505	4.821	16.237	17.529

Source: Maddison 1995, pp. 23 f., 104-116.

[a] Population of the territory of the Federal Republic (1989 boundaries). More adequate are the following figures: 1820 German States without Austria 24.905; 1913 Imperial Germany 66.978; 1990 Federal Republic with the former GDR 79.638. See also Maddison 1991.

Being the first industrial nation Britain had taken the technical lead in the second half of the 18th century. Early industrialising countries were the United States, Belgium, France and some German States (e.g. Saxony, Prussia). During the second half of the 19th century industrialisation gained momentum in the Netherlands as well as in Scandinavia, in parts of the Austro-Hungarian Empire, in Switzerland, Italy and Japan. In southern and eastern Europe, in Imperial Russia and in some other parts of the world industrialisation then had not become a country-wide process yet but was restricted to certain enclaves within a country. In spite of being scattered in many a place the process became a world-wide phenomenon, in so far as a country or region either itself underwent industrialisation or was involved in the international network of finance and trade which was dominated by the industrialised powers. This network did not only potentially maximise the world-wide production if one follows a Ricardian view but with its informal and formal empires (colonialism) it could be a means of economically exploiting large parts of the world to the benefit of the first industrial nations. A famous example is the Dutch 'Cultuurstelsel' (Cultivation System, 1830-1870) in colonial Indonesia. It meant a forced cultivation of colonial crops (e.g. sugar, coffee, tea, tobacco) destined for European markets. At the peak of this exploitation, between 1856 and 1866, the Dutch government's revenues were augmented by 30 million guilders yearly for a state budget of less than 110 million guilders. The modernisation of Dutch infrastructure (canals, railways, roads) could have been financed easily with this money (Maddison/Prince 1989, and Van der Eng 1993).

Although the self-sustained character of modern economic growth is still active a mere extension of the now existing industrial system of the western countries (the OECD-countries in the 1990s) to other countries might lead to a limit of growth. Even worse, the entailing gigantic pollution and the green-house effect might endanger the industrial system itself to break down. The industrial system has right from the beginning concentrated on new sources of energy, and the corollary of a widespread industrialisation would be the widespread use of (fossil) energy.[6]

Industrial Technology and Innovation

The following concentrates on certain innovations and industries, namely the steam engine, the iron and steel industry and the use of electricity.

During the industrial revolution the most important driving forces for innovations were focused on exploiting new sources of fuel and on economising on fuel consumption. Fuel was needed both for heating purposes and for generating mechanical energy. Thus the most important innovations of the industrial revolution in Britain were based on hard coal-consuming techniques. Britain was relatively well endowed with this raw material, whereas wood had become rather expensive already long before the 18th century. For simple heating purposes the (bituminous) hard coal was a perfect substitute for the hitherto generally used wood both in industry and household. It was as early as the 17th century that Britain experienced and tackled the problems, which the German economist Werner Sombart (1863-1941) labelled the 'wood brake' (Holzbremse). As a forerunner of the 'Limits to Growth'- admonishments this 'wood brake' threatened also the further growth of continental economies at the end of the 18th century. As has been put forward by Wrigley (1988) the inherent limits of the preindustrial 'organic economy' could not be overcome just by resorting to a new source of abundant heat energy, but new methods of deriving mechanical energy were required as well.

6 For a 20th century perspective, see Clark 1990.

The corresponding device for the mechanisation of production was the coal-consuming steam engine. As prime mover applied in large factories (e.g. for textiles) and as driving force of the railway and the steam-boat the steam engine became the embodiment of the industrial age. Nevertheless traditional sources of mechanical power, in particular the windmill, the water wheel and draught animals, remained important far into the 19th century (von Tunzelmann 1978, especially chapter 6). Even in Great Britain, which was rich in coal, the major innovations in textiles at the end of the 18th century had been developed for water- or horse-driven mills. 'With regard to individual innovations, one can note that virtually all the celebrated eighteenth-century inventions in textiles were created for either animals or simply man-power. Famous innovators of the British textile industry such as Hargreaves and Crompton were avowedly improving the lot of female spinners in cottage industry. Paul and Wyatt, Arkwright, and Cartwright all began with animals. Even for the spinning-mule, water-power was applied in incorporating the invention into factory industry before the steam-engine' (von Tunzelmann 1978, p. 160).

With these caveats in mind the history of the steam engine reveals essential characteristics of the interrelationship between the industrial revolution on the one hand and scientific and technological progress on the other hand. The steam engine is conventionally associated with the Briton James Watt (1736-1819) who got his first patent on this innovation in 1769. As with many inventions and their application to economic purposes Watt's achievement has to be placed into a long tradition of a process of trial and error (Mokyr 1990, pp. 84-90). Basically the first generation of steam engines rested on the simple knowledge that the atmosphere could be used as a source of power if a vacuum was created. Torricelli in Italy (1643/44), von Guericke in Germany (around 1660) and probably the Chinese and even people in ancient Alexandria (Heron, around 100 B.C.) knew about this principle and used it for fancy experiments. But not before the eighteenth century was this scientific knowledge translated into innovations, above all in England. After the French natural scientist Papin (1690) and the English amateur inventor Savery (1698) had developed prototypes of the 'atmospheric' steam engine, it was the English blacksmith Newcomen who for the first time constructed an economically successful engine, installed in a coal mine near Wolverhampton in 1712. In this machine condensation repeatedly created vacua through cooling the heated air in a cylinder. By this an alternate motive power drove a beam which was used to pump water out of mines. Newcomen's atmospheric steam engines were used in English tin and coal mines in order to drain the water. This innovation spread to continental Europe already during the first half of the 18th century. But the diffusion of this technology was limited because the machine's enormous appetite for fuel made it a costly device. That is why this steam engine was almost exclusively applied for the drainage of coal mines, a location where the needed fuel (coal) was available at cheap prices.

It was precisely the savings in fuel consumption which Watt's steam engine made such a success. The Watt engine raised fuel efficiency by nearly five times compared with Newcomen's design. This was due to several technical improvements: The piston cylinder was separated from the condenser, so that the cylinder could be kept hot constantly. Furthermore John Wilkinson's boring machines produced cylinders of great accuracy which helped to obtain a far better sealing compared to the Newcomen machine. These and other improvements saved fuel and therefore the use of the steam engine was less confined to locations close to a coal field. Watt also designed a transmission mechanism which converted the up- and down-motion into a rotative. In this way the steam engine became the prime-mover for machines in the textile industry and various other applications, such as the steam locomotive and a see-going vessel called steamer.

Watt was seemingly not that typical of the inventors and innovators, who shaped the technical change of the first industrial nation. As put forward by Mathias 'Most innovations were the products of inspired amateurs, or brilliant artisans trained as clock-makers, millwrights, blacksmiths...'. That obviously does not apply to James Watt, who was part of the academic community, after all. Watt was thus familiar with scientific experiments indeed. But it seems to be a yarn that his invention of the separate condenser arose out of listening to lectures on latent heat at Glasgow University.[7] So not even Watt may perhaps any longer be referred to as a man of science, who formed an exception to the rule that 'By and large innovations were not the result of the formal application of applied science, nor a product of the formal educational system of the country'. In particular 'the dozen and more inventors and improvers of techniques in steam power, and the entire pioneering of high-pressure engines, was in the amateur, and the blacksmith tradition' (Mathias 1983, pp. 121-130).

After Watt's patent had expired in 1800 a new generation of inventors and innovators improved the steam engine in its efficiency, which always meant saving fuel, and found various applications for its use. Technically most important was the creation of high pressure machines. In 1802, the Englishman Richard Trevithick built a steam engine with a pressure ten times as high as the atmosphere. In Europe and in North America in the course of the 19th century, numerous people constructed ever better steam engines. And 'better' is measured in terms of fuel input in relation with power generation. Besides high pressure it was the principle of compounding which saved fuel. Compound steam engines comprised several cylinders where the same steam could be used subsequently.

The diffusion of the steam engines depended not only on their fixed costs, i. e. the price of the machine, but also on their variable costs, i.e. the costs of coal consumption. These costs changed a lot over time, among different types of machines and among geographical locations, i.e. depending on the access to a coalfield. And of course the cost relation towards alternative (traditional) sources of power remained crucial, i.e. wind, water, animal and human power potentials. In essence all these factors are considered by von Tunzelmann's study (1978). He briefly also compares Britain with the United States and Belgium. The Newcomen steam engine spread fast in Britain and within decades even in continental European countries. It was used for pumping water out of coal mines. According to an estimation around 1800 roughly 2500 steam engines had been built of which about one third had been designed by Watt. It was not before the 1790s that steam engines were used on a large scale in textile factories. The heyday of the steam engine was yet to come during the 19th century. Eventually not only stationary engines were used in factories, mines etc. as prime mover, furthermore steam engines served to improve transport over land (*railway*) and on water (*steam-ship*) considerably.

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[7] von Tunzelmann 1978 (p. 11) quotes the research of Cardwell.

The other major coal-consuming technology involved the iron and steel industry.[8] 'How do we assess the importance of the iron industry in the industrial revolution? The economist's test of the importance of any invention is its substitutability: if it had not been invented, would another technology have done? By that criterion, the steam engine and cotton look less of a strategic invention than the advances in iron. It is conceivable to imagine an industrial revolution based on water power and linen or wool - in fact in many places that is precisely what happened. There was no substitute for iron, however, in thousands of uses, from nails to engines. As its price fell, iron invaded terrains traditionally dominated by timber, such as bridges, ships and eventually buildings' (Mokyr 1994, pp. 26 f.).

Only a few parts of the world lack iron ore. With charcoal (made from wood) serving as a fuel this iron ore could thus be molten into iron nearly everywhere. So the traditional iron and steel industry was widely spread all over the world. As soon as hard coal was used for producing iron and steel the regions endowed with plentiful coal deposits became the primary sites of heavy industry. But even in pioneering Britain it took nearly a century before hard coal had supplanted charcoal as a fuel for smelting and refining iron (Hyde 1977). Major technical problems made it difficult to find an economically viable alternative for the traditional charcoal technology.

The simplified Scheme 1 allows a survey of the transition from charcoal to hard coal in the primary iron industry at a glance.[9] In liquid state pig iron (1. stage) could be cast into forms for obtaining cast iron products. In order to shape iron with a hammer pig iron had to be refined (2. stage). Refining meant a reduction of the carbon content thereby turning the brittle, hard pig iron into a tough, but soft wrought iron. Shaped into bars it was sold e.g. to smiths, who produced agricultural implements, horse shoes etc.

Scheme 1 *Primary Iron Industry*

Stage of Production	Process		Product
	traditional	modern	
First Stage	Smelting in the blast furnace		pig iron
	with charcoal	with coke	
Second Stage	Refining		wrought iron
	in a hearth with charcoal	in a puddling furnace with hard-coal	
	Shaping		bar iron (rails)
	by the hammer	by a rolling mill	

8 See the excellent survey by Church (1994) on the different views concerning the role of the iron industry during 'The Industrial Revolutions'.

9 For a comprehensive analysis of the introduction of hard coal technologies into the iron industries in Britain, Belgium, France, and Germany see also Fremdling (1986).

Around 1700, the British primary iron industry lagged far behind Sweden, the world market leader of that time. The small British sector produced expensively and could survive only behind protective walls. But in spite of the import duties the growing indigenous demand for wrought iron was mainly met by imports from Sweden and later from Russia as well. Still in 1788, those imports stripped out the domestic production. Not before the 18th century did the British primary iron industry change fundamentally. After a lengthy process of trial and error the Briton Abraham Darby of Coalbrookdale in 1709 succeeded in substituting hard coal (or its derivate coke) for charcoal in the blast furnace. He had found an economically viable way of using coke smelted pig iron as an input for cast iron products. For wrought iron the input of charcoal pig iron was still cheaper until well into the second half of the 18th century. The diffusion of coke-blast furnaces in Great Britain did not accelerate before the 1750s. First of all it was the demand for cast iron products which propelled this diffusion. Especially for construction purposes cast iron served as a substitute for timber, bricks and stones. The famous iron bridge crossing the Severn close to Coalbrookdale was built in 1781. It is a still existing monument of this cast iron age.

Throughout the 18th century, prices for charcoal increased whereas hard coal became relatively cheaper. It was thus ever more rewarding to find a process which allowed the use of hard coal for the production of wrought iron. But a contact between the hard coal and the object heated could produce undesired chemical reactions, as impurities in the coal, such as sulphur and phosphorus, could be transferred to the melting metal. This contamination could make the metal brittle and technically inferior to the metal refined with traditional charcoal. So the main technical problem was to keep hard coal and the molten pig iron apart while refining the iron. Nobody knows how many attempts failed before this problem was finally solved. It took several generations to overcome these difficulties through trial and error methods. Most likely the Wood Brothers already in the 1760s had found an economically viable way. They used clay-pots, which separated the reheated pig iron from the hard coal, thus avoiding undesired chemical reactions during the refining process. Probably half of the British wrought iron was produced by applying the potting process of the Woods when Henry Cort got his famous patent on the puddling and rolling process in 1784. The inside of a bricked-up puddling furnace consists of three parts: low walls separate the bowl or working area from the fire grate on the one side and from the chimney on the other, thereby keeping the hard coal apart from the iron. Built only half high, these walls leave the cavern of the entire furnace open so that the hot firing gases pass over the pig iron in the smelting chamber (bowl area), heating and smelting it, and then escape through the chimney. Puddling remained a handicraft, with very strong men stirring the molten mass by hand and turning and lifting the refined iron.

In addition to this new refining process Cort also introduced rolling as a superior method of shaping the wrought iron into bars. The technologies based on hard coal spread very fast in Great Britain. Riden (1977) estimated that in 1750/54 just 7% of the pig iron were smelted by using coke (made from hard coal) in the blast furnace, 1785/89 it made up nearly 90%. At the beginning of the 19th century after the Napoleonic Wars, Britain boasted of the largest and most productive, thus cheapest primary iron industry on the world. The former disadvantage of

Britain, namely the expensive wood, had made itself flagrantly felt at the beginning of the 18th century but a century later, it had turned into an advantage, namely introducing hard coal based technologies. This development was possible only because Britain gave an innovative response to her resource endowment.

Which were the consequences the process innovations of the coke using blast furnace, the puddling furnace and the rolling mill had on the iron industries in other countries? If these innovations were highly superior to the traditional procedures not only technically but economically as well the new techniques should have spread rapidly. This implies that the old-fashioned iron industry based on charcoal should have perished fast. But just this did not occur for quite a long time. Traditional or partly modernised procedures could endure very well within their districts and their markets from of old. Moreover, when spreading over continental Europe or North America the new techniques did not follow the British model strictly, but reacted in different ways. The following examples of adaptations to the British hard coal techniques in Prussia, France and Belgium exemplify the fundamentally different ways of reacting to the British challenge. An inclusion of additional countries would not have yielded more principal information on the transfer of this important technology of the first industrial revolution. For more information on other European countries, North America and Japan (also on the adoption of liquid steel processes in the second half of the 19th century) see the articles in Church (1994); furthermore Temin (1964), Allen (1977), Inwood (1992), and Abe/Suzuki (1991).

At a very early time, the state-owned ironworks of Malapane, Gleiwitz and Königshütte (Krolewska Huta) in Prussian Upper Silesia were the very first on the continent to continuously use coke for smelting pig iron. Upper Silesia was very well endowed with hard coal, but was also rich in wood. Starting already in the 1790s the early transfer of hard coal technology is rather uncritically widely esteemed a striking success. But coke smelting remained a heterogeneous element in an economically viable but technically rather backward sector for quite a long time: In its technical backwardness the Upper Silesian wrought iron industry did neither apply the then available modern techniques of employing hard coal (namely potting and puddling) nor did it resort to more efficient methods of charcoal technology. The technical problems of coke smelting were solved indeed, but still these ironworks did not make profits by this production. Prussian technocrats are to blame for introducing coke smelting that early. They had been mistaken when imagining a programme for industrial development to be capable of putting the British model quickly into practice behind there in Upper Silesia. Inconsiderately the Prussian technocrats had jumped to the conclusion that technical feasibility meant economic success. It did not, and thus coke smelting in Upper Silesia exerted neither any serious consequences on the rest of the iron industry there nor on the position Upper Silesia had towards other regions until the 1830s.

Before the prohibitive duties of 1822 were levied only a few French ironworks made efforts to follow the British model.[10] The coal fields of Creuzot for instance had blast furnaces already

[10] On the French iron industry see among others the studies by Gille (1968), Vial (1967), and Woronoff (1984).

in 1783/84. But before the brothers Schneider in 1836 set out to make Le Creusot one of the most successful engineering and iron works of France the enterprise had been somewhat of a failure. The conditions after 1822 seemed to favour establishing British type ironworks in France. By then imports from Britain had shown that there was a demand for hard coal iron. With the custom policy guaranteeing a high price level big profit seemed to be in prospect. In expectation thereof ironworks shooted up in the coal districts of the Loire valley and the Massif Central. Following the British model they were built as big ironworks straight away comprising several stages of production. But these new establishments went without economic success until far into the 1830s. Technical problems at the outset were solved bit by bit indeed but the new locations presented serious shortcomings: Other than in Britain the iron ore had to be transported from afar, which raised the costs of production enormously. Moreover the sites of the new iron industry were located remote from the centres of consumption, which made the sale dearer. To make matters worse in these centres the new products had to compete with those the traditional or partly modernised iron industry offered in a superior quality. The newcomers could not undercut the prices of the old-established firms low enough for them to enter the markets. Thus for a long time the changing economic structure did not entail the decline of the traditional iron producing regions.

Dutch-Belgian Wallonie was well endowed with hard coal. It was the only continental European region to follow the British model successfully even before the construction of railways (Reuss et al. 1960). Since the middle of the 1820s numerous works comprising coke blast furnaces as well as puddling and rolling mills were built there in the coal mining areas around Liège and Charleroi. Excelling the others the factory of the British-Dutch-Belgian entrepreneur John Cockerill at Seraing as early as 1825 integrated all stages of production from engineering to the supply of raw materials. The natural locational factors of Wallonie were similar to those in British iron producing regions with ore and coal situated closely together. Transportation costs and moderate protective duties screened Wallonie from the British competition while the then Dutch government pursued an ambitious programme for industrial development fixed on the British model.

Thus, except for Wallonie, the first efforts to transfer the British high-technology to the continent by building coke blast furnaces solely or as part of integrated ironworks failed economically until well into the 1830s. But beyond imitation the British model urged on the traditional iron industry to apply various strategies of adaptation. Hence this sector did not remain passive at all, but it underwent a development known from other branches as well, for instance from sailing ships: A technique becoming obsolete in the end reaches its highest technical and productive level shortly before it disappears. Accordingly calculations made for Sweden, the German Siegerland and Württemberg show that smelting iron traditionally with charcoal increased its productivity considerably in the decades from the 1820s to the 1850s which is exactly the crucial period for the modern iron industry spreading over the continent (Fremdling 1986, pp. 155-161). The improvements were achieved through extraordinary retrenchments on charcoal having the highest shares in the costs of smelting iron. In some traditional iron producing areas even the output grew enormously. Only in the 1850s did this growth reveal itself as a short-lived success. And even than several contemporary experts did not at all foresee that the traditional iron producing areas that disposed of nothing but wood and iron ore would more or less sink into insignificance by the side of the large-scale technology coming from Britain.

The traditional iron industry struggled for survival by both increasing the productivity of smelting iron with charcoal and by elaborately integrating parts of the new technique. The small forges could for instance substitute the new puddling furnace for the old refining furnace without changing the rest of the operations. Detached from the other modern techniques from Britain the craft of puddling began spreading over many regions of traditional iron industry already in the 1820s. As puddling furnaces were fuelled with hard coal the charcoal was left for the blast furnaces now and the rise in charcoal prices was slowed down. These partial modernizations were widely spread over the most important regions with a traditional iron industry in Germany and France, namely the Siegerland and the Champagne. The bar iron produced by mixing old and new techniques was of as good a quality as the traditional iron but much cheaper. At the beginning the iron made by use of hard coal through and through was of inferior quality and thus had to compete hard against both the traditional iron and the new product of the technique combination. In the middle of the 1830s, i.e. before railway construction took off, this combination of 'old' and 'new' explains why already roughly half of the bar iron in France and one third in Prussia was processed in the modern puddling furnace (using *hard coal*), whereas less than twenty per cent (France) and ten per cent (Prussia) of the pig iron were smelted in a modern *coke* blast furnace.

In the middle of the 1830s, continental Europe began constructing railways. This ensured the crucial demand to the modern iron sector in Germany and France whereas in Belgium the further expansion of the modern iron industry was powerfully supported by the railways. The prohibitive duty levied until the 1850s hindered French railway companies from buying British or Belgian rails. Railway demand made modern ironworks in the French coal mining areas economically viable for the first time. For rails did not require wrought iron of the highest quality, which the traditional or partly modernised ironworks offered, but low-quality iron sufficed absolutely. Except for the deep economic slump after the Revolution of 1848 the increasing demand made both the traditional and the modern iron industry expand well into the 1850s. The individual French ironworks made different use of this prosperity. So modern works such as Decazeville made themselves closely dependent on railway construction thereby failing to gain a footing in other segments of the market. Some others such as Le Creusot got beyond rail production and learned how to make hard coal iron in ever increasing qualities and to offer it at prices low enough for them to enter into markets, which had hitherto been the domain of the traditional iron industry. In the long term this process would have ruined the iron production based on charcoal in any case. But in France the customs policy induced a sudden decline of that industry around 1860. Already in the 1850s Napoleon III had taken measures to reduce the tariffs or to undermine the protective customs structure. In 1860 the Cobden-Chevalier-Treaty between Britain and France finally established a system of rather moderate tariffs. The production costs of the *traditional* ironworks were too high for them to keep their ground against the sudden import competition. Within only a few years they shrank and sank into insignificance. Neither were all *modern* ironworks up to the tough competition from abroad. Decazeville, once the greatest rail producer of France, descended to a mere coal mine. Having been forced to drastic adaptations in the late 1850s the outlasting modern French iron industry consolidated and expanded rapidly during the 1860s. Now that the railway had connected producers and consumers the remote location of the modern iron industry within the coal fields was no longer an unbridgeable gulf.

From the beginning of railway construction onwards the German iron industry partly took a similar course, but there were significant differences as well. Unlike France the German Customs Union admitted imports to a large extent. Thus Germany at first imported the railway iron from Belgium and Britain. Under the protection of an import duty on bar iron, moderate though, the coal districts soon attracted rail producers. In Upper Silesia and Saarland large ironworks were established comprising all stages of production whereas the Rhineland and Westphalia (the Ruhr basin) built mere puddling and rolling mills at the beginning. They worked up imported coke pig iron from Britain and Belgium. Little by little these modern works gained the markets of the traditional iron industry. In parallel with France, in the 1860s, the old sector hardly counted any more. But having had to cope with the import competition already since the early 1840s at the latest the old-established German iron industry was spared the precipitation into mere nothing the French had to endure, but it shrank rather smoothly instead. The Siegerland adapted to hard coal technology and thus survived even if degraded to a secondary centre. Interlacing with the Ruhr district as the predominant new centre the Siegerland provided ore and pig iron and received coal from the Ruhr in exchange. The Ruhr district was the region to generate by far the most dynamic forces of evolution. Among all iron producing regions mentioned so far the Ruhr district was the very last to adapt to *all* new hard coal techniques. Puddling and rolling mills had long been established before coke smelting advanced towards the Ruhr in the 1850s. But then the area achieved the highest rates of increase of all. In Table 2 it is shown how the hard coal technologies spread in the three continental countries under consideration.

New major technological changes came up in the second half of the 19th century with the introduction of liquid-steel production. These techniques finally replaced the puddling furnaces. It then became common to refer to all types of wrought iron as 'steel'. In 1856 the Briton Henry Bessemer (1813-1898) got a patent to produce steel directly from the molten pig iron by blowing air through it. For this way of refining no additional fuel was necessary when the metal was kept liquid after leaving the blast furnace. Bessemer and others (e.g. the American William Kelly and the Briton Robert Mushet) had to solve quite a lot of problems to produce a commercially viable steel. At first Bessemer's steel did not turn out to be the cheap substitute for the expensive crucible steel as had been expected. Furthermore it took years of trial and error to improve the quality of the steel before it could be used for the production of rails for the railway. (At length, the Bessemer steel rails became more tenacious and elastic, thus more durable than rails rolled from puddled wrought iron.) Secondly another problem was not solved for more than two decades after Bessemer's invention. Pig iron smelted from phosphoric ores could not be refined in the Bessemer converter. Not before 1878 did the Britons Sidney Thomas and Percey Gilchrist find a solution to this problem. By adding limestone to the firebricks in the converter the harmful phosphorus was neutralised. This caused a chemical reaction which resulted in a basic slag. In Germany where the Thomas process spread rapidly this basic slag "Thomas-Mehl" became a foremost artificial fertilizer in agricultural and was even exported in large quantities, e. g. to the Netherlands. With this basically slight technical modification of the converter the rich phosphorus minette deposits in French/German Lorraine could be used for the rapidly expanding production of Thomas steel.

Table 2 *Iron Production in Belgium (B), France (F) and Prussia (P), 1836-1870, thousands of metric tons and percentages*

Year		Pig Iron Production by coke or mixed fuel		Bar Iron Production by hard coal	
		1000 tons	(%)	1000 tons	(%)
1836	B	101.4-115.8	67.5-71.5		
	F	308.4	15.0	210.6	47.3
	P	88.7		50.5	32.1
1837	B	118.1	72.1		
	F	331.7	15.9	224.6	51.0
	P	99.5	9.6	58.7	31.8
1842	B	81.3	90.8		
	F	399.5	25.6	284.8	61.1
	P	101.0	18.0	79.3	39.5
1847	B	248.4	89.5	80.9	
	F	591.6	42.6	376.7	74.3
	P	137.9		158.5	70.2
1848/1850	B	151.5	89.8	65.9	
	F	430.8	40.9	255.3	71.4
	P	126.7	22.7	117.8	59.3
1851/1860	B	274.3	95.7	143.1	
	F	780.0	58.6	480.0	79.9
	P	305.5	38.3	239.8	85.4
1861/1870	B	442.2	99.2	358.8	
	F	1191.5	84.1	767.0	90.6
	P	819.9	91.5		

Source: Fremdling 1986, p. 359.

In the middle of the 1860s another refining method was introduced. For that open hearth or Siemens-Martin process the experiences and experiments of several experts in three countries (France, Germany, Great Britain) combined. In a furnace the molten metal is exposed to extremely high temperatures. Without being stirred by a puddler the metal is refined. Refining iron in the open hearth takes very long, but the slowness leaves more time to control the process, so that the yield is of superior quality. Another important advantage is that scrapped iron serves as a major input in the open hearth. But similar to the Bessemer converter in the beginning the open hearth process could not be applied for refining pig iron produced from phosphorus-bearing ores. And likewise, the 'basic' process for which the furnace was lined with basic materials, was applied to the open hearth not before 1888.

In contrast to the diffusion of the earlier innovations (namely coke smelting, puddling and rolling) the new liquid-steel processes spread in France, Germany, Belgium and the United States without a considerable time lag from Britain. Puddling was not replaced immediately, though. The decision of substituting liquid-steel processes for puddling depended on economic considerations (cost and price differences), as well as on the physical properties of the new steel products. As only the basic variant of the open hearth process rendered a steel as good as the soft puddled iron in Germany e.g. puddled iron dominated until 1889 thereafter declining rapidly. A highly famous building made of puddled iron is the still existing Eiffel-Tower in Paris, which was completed in 1889.

The first important customers for the new steel were the railway companies. By the beginning of the 1860s, it had already been proven that the stronger Bessemer rails would last longer than the softer, but still cheaper, puddled rails. During the 1870s the efficiency of the converter was improved considerably, so that the prices for Bessemer rails dropped. Not only could Thomas steel do with a different input but it furthermore boasted of properties different from Bessemer steel. The soft Thomas steel allowed a diversification of end products. Now that they could produce merchant iron, wire, tubes, pipes, and sheet metal out of Thomas steel, the steel mills gave up their puddling furnaces for good. It was mainly on the European continent, particularly in Germany, that steel mills specialised on Thomas steel. Steel consumers here were content with this cheap mass product although it was of medium quality. After 1900, however, most of the new steel mills were open hearth plants. Major customers of the high quality steel were shipyards. This partly explains why British steel mills had switched to the open hearth process earlier and on a larger scale. In the course of time Germany and Britain specialised on different market segments: production of medium-qualities in Germany, of high-qualities in Britain (Wengenroth 1986).

At the turn of the century, the iron and steel industry was regarded not only as a major sector in modern industrialised countries, but also quite often as embodiment of a nations cultural achievements and its power, as the saying goes: 'Iron is the State' and the German technical historian Ludwig Beck stated that '...the progress of the iron industry is so closely connected with any progress in modern culture and civilization, that the very consumption of iron per capita presents the proper yardstick of industry, welfare, and the power of nations' (Beck 1899). In this overweening estimation the fact that America and Germany surpassed Britain's iron and steel production has often been seen as symbolic of the British decline. By 1890, the United States had taken the lead in producing pig iron and steel, while Germany had surpassed Britain concerning steel in 1893, and concerning pig iron in 1903. Until far into the 20th century, coal and steel remained strategic sectors indeed. Not by accident did the West European unification begin with the founding of the European Coal and Steel Community.

The salience of the steel industry substantiates the paramount importance of hard coal as new source of energy. Although hard coal had been available for thousands of years it had been of minor importance before the industrial revolution. Then even regions or countries less endowed with this raw material could proceed to coal consuming technologies (Fremdling 1996) because cheap transport became available in the second half of the 19th century. This was the consequence of improved coal consuming steam engines applied in locomotives and ships. Here we have a good example for industrialization being driven by circular chains of causes. Cheaper transport widened the markets for coal sales and allowed more and more the application of coal consuming techniques remote from the coal mining districts. This in turn increased output of coal in the mining area and via economies of scale and new connections transport became ever cheaper. Thus the combination of forward and backward linkage effects caused self-sustaining growth in the world economy.

In the form of coal tar the 'new' raw material hard coal furthermore served as a major input for a modern organic chemical industry. In 1856 the Briton William Henry Perkin (1838-1907) accidentally discovered the synthetic version of the dyestuff aniline purple when trying to produce artificial quinine, a medicine against malaria. Aniline purple, called mauveine, replaced in the long run the natural dye mauve. This discovery marked the beginning of numerous efforts to find dyes based on coal tar. Until then dyes had only been obtained from plants or animals. Coal tar was a by-product (or better: a waste-product) when producing lighting-gas from hard coal. In the following decades mainly German chemists synthetised more and more artificial dyes (e.g. alizarin, indigo), which were mainly used in the textile industry. The still existing German giant enterprises 'Bayer, BASF, and Hoechst' developed their strength on artificial dyestuffs. In chemistry German firms and scholars at universities took the technological lead. Around 1880 about half of the worldwide production of synthetic dyes came from Germany. Until the eve of World War I (1913) the share comprised between 80 and 90 per cent.

A new source of energy has been exploited from the end of the 19th century onwards, namely crude oil. In the middle of the 20th century it had replaced hard coal to a large extent, but before 1913, the direct substitution had been rather limited. In 1913, crude oil provided no more than 5 per cent of the worldwide energy consumption, whereas hard coal still contributed roughly three quarters to the energy supply (Clark 1990, p. 31). Of course the advent of the automobile resulted in rapid increases of gasoline from crude oil.

As this contribution focuses on the industrial revolution no independent account of scientific progress as such is due. The relevant question remains as to what extent sciences were related to technical progress at that time. Kuznets claimed that modern economic growth was based on the epochal innovation of 'the extended application of science to problems of economic production' (Kuznets 1966, chapter 1). As against that most economic or technical historians maintain that this hardly applies to the industrial revolution proper: Until far into the 19th century, no decisive influence on technological progress is ascribed to advances in scientific knowledge (Cameron 1989, p. 195). And until about the 1860s, scientists rather strived to explain the practice of industrial achievements afterwards than to put scientific knowledge itself into practice, exceptions notwithstanding. These scholars even went so far as to claim that scientists then learned more from practice than the other way round. A more balanced view, not contradicting this basic statement, was put forward by Joel Mokyr (1990, p. 113): 'It is widely believed that before the middle of the nineteenth century, technological progress moved more or less independently of scientific progress, and that since then the interaction between science and technology has gradually become tighter. As we have seen, this view is only partially correct.

Science, and especially scientists, were not totally irrelevant to technological change before 1850. Between 1600 and 1850, technology learned some things from science, and more from scientists. In few cases, however, can we conclude that a particular invention depended crucially on a breakthrough of the scientific understanding of the chemical or physical, let alone biological, processes involved. After 1850, science became more important as a handmaiden of technology. A growing number of technologies, from waterpower to chemicals, depended on or were inspired by scientific advances. Yet the number of technological breakthroughs that were purely empirical has not declined, even if the *relative* importance has fallen'.

When discussing the connections between science and technology during the British industrial revolution Ian Inkster (1991, pp. 69 ff.) makes out a 'seeming confusion' among different scholars. In his solution he maintains firstly that already during the British industrial revolution certain fields of endeavour owed a considerable debt to science, like the chemical industry. He secondly puts forward 'that the availability of specific scientific and technical information was important in creating the host of incremental and adaptive innovations which in many instances followed upon important inventions...'. If furthermore this kind of information was gradually available among different social groups and localities in Britain this would explain why precisely in the British society the industrial revolution and its related technical progress can be viewed as both driven by experience and by the application of science. If an important law of nature, say that of the leverage, is fully embodied in a machine this law becomes a common information and can be applied by people who don't know the underlying scientific formula. If this kind of information is not acquired predominantly by any formal education you cannot force a clear-cut distinction between science and empiricism.

In the middle of the 18th century, England disposed over more 'technicians' than continental countries. All those engineers, mechanics and craftsmen had been trained on-the-job or as apprentices without much of a formal education. Technical knowledge, however, was widely spread through informal lectures, scientific societies, and technical literature (Mokyr 1990, pp. 240 f.) and above all through handling technical products and processes. The British comparative advantage may also explain why Britons rather often achieved the implementation of inventions, even if these originated from the continent. For one thing, the basic scientific knowledge of that time thus seems to have been widely engrained in Britain (Inkster) and for another thing, British science 'was predominantly experimental and mechanical, whereas French science was largely mathematical and deductive' (Mokyr 1990, p. 242, referring to Kuhn). This British interrelation between science and practice proved a highly favourable environment for the application of science, innovation and improvement.

Even at the time of the first industrial revolutions, branches as the electrical and chemical industries required a high degree of scientific knowledge and training. Until the end of the 18th century, electrical phenomena had widely been regarded as curiosities before they became a field of serious science. During the first half of the 19th century, several electrical phenomena, which finally proved useful for practical purposes, were hence discovered by research. In 1807, the Briton Davy discovered electrolysis, which was used in the electroplating industry since the 1830s. In the following decade his assistant Faraday made a host of discoveries and inventions not only in the field of electricity. Based on the principle of electromagnetism he invented the electric motor in 1821 and the dynamo in 1831. As an economically efficient generator still lacked electric motors were not cheap enough to compete with steam engines.

As a consequence, electricity did not come into its widespread use through power transmission but through the electrical telegraph. Several inventors are associated with this message transmission, one was the American Morse, who since 1837 developed his needle system and the code named after him. As neatly described by Mokyr (1990, pp. 125 f.) 'The telegraph, like the railroad, was a typical nineteenth century invention in that it was a combination of separate technological inventions that had to be molded together.' It took decades of subsequent inventions and improvements before the long-distance telegraph over land and below the sea became reliable. Hardly one third of the transatlantic cables laid before 1861 had survived in this year. Besides its military, political and personal use to transmit messages, the telegraph for the first time allowed a fast coordination of international financial and commodity markets. Like the railway it was a network crossing state borders and as such required international cooperation. The ensuing International Telegraph Union of 1865 was one of the several bi- and above all multilateral agreements concerning railway and postal services and foreign trade.

Major problems had still to be solved in the generation of electric energy. The breakthrough came in the 1860s when several inventors independently discovered the principle of the self-excited generator. One of them was the German Werner von Siemens, who did not detect the principle by theoretical reasoning, but rather by intuition when constructing magnoelectric detonators for the Prussian army in 1866. Siemens had made a fortune out of telegraphy and was hence familiar with applying electricity. Combining all the virtues of a successful entrepreneur, technician and scientist Siemens realised his commercial possibilities. From 1868 onwards, his firms successfully sold small dynamos. The Belgian Gramme was the first to construct and sell larger dynamos in the 1870s. With the coming and improvement of dynamos from the 1870s onwards ever more factories, stores, theatres and public buildings installed the well known arc lamps for lighting. Between 1878 and 1880, the Briton Swan and the American Edison perfected the incandescent electric lamp almost simultaneously. The new bulb substituted for arc lighting and created a boom in the electric industry both in Europe and the United States. One should keep in mind, however, that for further decades gas (made from hard coal) remained a viable alternative for electric illuminants. Other applications for electricity where the electrical street car and small electrical motors for factories. And soon the way for household appliances was paved as well.

Before the coming of centralised power stations every building with electrical lighting possessed its own power station, where the generators were driven by a steam engine, a gas motor or even a water wheel. In the long run, centralised power stations with networks spanning several quarters of a city or a whole municipal community became the rule. The first was opened by Edison in New York City in 1882, Berlin followed in 1885. For these 'public' networks spanning municipal property the approval of the community was necessary. When the enterprises turned out highly profitable ever more municipalities ran the networks and power stations themselves. Alternating current came out victor from the battle among different current systems because it was better suited for long distance transmission. At the end of the 19th century, even the most powerful steam engines turned out a serious bottle neck in generating electricity. The limited rotational velocity of the reciprocating steam engine did not reach the high speed required by a dynamo. It was, however, still steam which solved the problems of generating enough electrical power: Hard coal heated the water in devices as the steam turbine, which had been developed in the 1880s by the Briton Parsons and the Swede de Laval. Furthermore there was the hydraulic turbine which already in the 1820s and 1830s had been developed by French engineers to convert the force of falling water into energy. In the 1870s, in south-eastern France this device was already attached to a dynamo. As put forward by Cameron (1989, pp. 198 f.) 'This apparently simple innovation had important long-range consequences, for it enabled regions poor in coal but rich in water power to supply their own energy requirements'. The hydraulic turbine finally freed the generation of electrical power from coal after the steam engine had tied it for decades to the most important source of energy of the industrial revolution, namely hard coal.

The application of electricity in the course of the 19th century anticipates a few features characteristic of the so-called 'second industrial revolution'. First of all, inventions and innovations seem to have been much more firmly based on scientific progress than during the first round of the industrial revolution. (The empirical element of trial and error in solving practical problems remained very important, though.) Secondly, scientific and technological progress became an international phenomenon with different people searching for the solution of the same problems in places all over Europe and the United States. As a consequence, in a *convergent* development, new inventions were implemented in the leading industrial powers without any significant delay. And thirdly, the use of electricity itself turned out a large technical system comprising the generation, transmission and transforming of power into its final uses such as kinetic power, light or heat. The interrelatedness with other branches of industry (e.g. the coal-fired steam engine) required a highly developed industrial system with a complex network of complementary and substitutional devices. Convergency notwithstanding, at the same time there were divergences as well. In a *divergent* development, the structure of networks like these revealed different styles among countries.

In the second half of the 19th century the *American System of Manufactures* emerged, and for some it was distinctly different from the British or European skill-intensive system (Habakkuk 1967). Due to higher labour costs (thus different factor costs as compared to Europe in general), capital intensive mass production characterised the American industry. It has often been maintained that in the search for labour-saving inventions the American system generated more and faster innovations from the late 19th century onwards than their European counterparts. Among others the professional inventor Thomas A. Edison (1847-1931) - *electricity* -, the automobile tycoon Henry Ford (1863-1947) - *assembly line* -, and Frederick W. Taylor (1856-1915) - *scientific management* -, stand as synonym for a superior American manufacturing system indeed (Hughes 1989). For many people this 'competitive managerial capitalism' (Chandler 1990) has become the model of industrial achievement after Britain's relative decline as the industrial super power after the first round of industrial revolutions. Recent studies corroborate that labour productivity in American industry was significantly higher than in England as early as the first half of the 19th century (Broadberry 1994). To what extent could the *American System of Manufactures* have been copied and to what extent did it form the technological frontier? First of all the American practice was a reaction on a specific resource endowment (scarce labour, abundant land and natural resources) with corresponding relative factor costs. Thus a *simple* copy or transfer of American technology into other countries was limited anyway. Furthermore different technical systems or styles of technique among different societies do not solely depend on different factor costs but they probably also represent anthropological and of course institutional differences among peoples (Radkau 1989, p. 37).

The impact of educational institutions on the economic performance of a nation is not questioned. The following deals with the formal professionalised higher education in the field of sciences and engineering and its impact on technological progress. Twisting this argument many historians jump to the conclusion that Britain's alleged relative decline as compared to Germany and of course to the United States must have been caused by a somehow inferiour scientific and technological formal education. Prior to 1914, 'A nation such as Britain, with its wide 'audience' for science, might actually seem to be falling behind in science (...) But in terms of the creation of new, abstract knowledge, in terms of the diffusion of information through the social system and in terms of the sustenance of routine 'ordinary inventiveness' [....] throughout the industrial system, Britain may well have been significantly ahead of most nations at this time' (Inkster 1991, p. 130). In this line of argumentation the governmental interventions in some fast growing nations for building modern universities and other formal institutions might be regarded as an indication that these countries (e.g. Germany, Japan or Russia) simply needed more help to both concentrate and professionalise their small base of modern science. To sum this seeming contradiction up: investments in formal education are necessary for economically poorly performing societies in order to acquire knowledge for technological progress, to be sure. But those investments are no measure for the level and diffusion of technological knowledge in a given society as traditions other than a formal education might have built up and spread that knowledge as well like in Britain.

The relation between scientific knowledge and industrial production became ever more professionalised and moreover institutionalised. One outcome of the French Revolution and the government of Napoleon was the creation of specialised schools for science and engineering or applied research. The Ecole Polytechnique (1794) and the Ecole des Arts et Metiers (1804) served as model for other countries. Similar technical (high)schools or technical universities (later they acquired the same status as the classic universities) were founded in the Habsburg monarchy in Prague (1806), Graz (1811) and Vienna (1815), in Swiss Lausanne (1853) and Zurich (1855), and in Delft (1863) in the Netherlands. In particular in Germany these institutions were established or existing technical schools adopted partly the curriculum of the French model. As Germany was not a unified centralised state all the independent medium-sized states not only had their classic universities from old but now they, mostly in their capital cities, possessed their technical university, among them Dresden (1828) in Saxony, Karlsruhe (1825) in Baden, Stuttgart (1829) in Württemberg, Darmstadt (1836) in Hesse, Munich (1868) in Bavaria and Hanover (1831) in Hanover. In Prussia the 'Technische Hochschule Charlottenburg' of Berlin (1879) was the successor of two older technical schools for architecture and manufacturing. At these 'Technischen Hochschulen' students got a formalised training in applied sciences in close cooperation with industry. E.g. the 'Technische Hochschule Berlin-Charlottenburg' worked close together with the electro-technical firm of Siemens. The chair for this field of science and engineering was sponsored by the same firm and the exchange of staff members guaranteed a mutual reenforcement of science and its application. In this educational system the engineer was thus scarcely a man of practice any more but rather became a professional with a formal academic education. With the celebration of the one hundred year anniversary of Humboldt's Berlin University in 1910 another institutional reform in research was carried out in Berlin: i.e. the foundation of the 'Kaiser-Wilhelm-Gesellschaft', today named 'Max-Planck-Gesellschaft'. Here government and wealthy industrialists, bankers etc. jointly sponsored top-level independent research institutes in sciences. With this institutional innovation e.g. Albert Einstein could be attracted to Berlin where he in 1913 became director of the Kaiser-Wilhelm-Institute for Physics. The 'Technische Hochschule' and the German university in general became the very model for university reforms in other advanced countries. The most prominent example were the United States where in the 1870s educators turned to Germany rather than England or France when reforming higher education. Subsequently other countries fell in line as well, including Britain and France.

Britain was the first country to introduce a patent law as early as in 1624. In France, a similar law was not enacted before 1791 and the other continental countries followed even later. In Germany an effective national patent law came into being in 1877. The economic impact of such a law might entail positive as well as negative effects on the economic development. The pro is simple and straight forward: patent laws goad to technological progress. For the pioneer entrepreneur in a competitive system has to be allowed to reap the profits of his innovation. Otherwise there is no incentive for him to innovate. But the con is just as simple and straight forward: being protected by a patent the innovation cannot be copied by competitors. Hence the diffusion is delayed and furthermore, the patent-holder has less incentives to improve on his original invention/innovation. Because of this ambiguity governments in market-oriented economies made the compromise as to restrict this protection to the limited period of around 15 years.

Great inventors (e.g. Watt or Bessemer, who reaped their profits under the patent protection indeed) are often advanced in order to praise the benefits of patent laws. The drawbacks of such an institutional arrangement probably preponderate, though. Holding a patent and not effectively using it might very well block any technical progress in this field. The famous example is Watt himself, who hampered the development of high-pressure steam engines (Mathias 1983, p. 123). Another problem arises when several people are involved in an invention. Moreover various improvements have often to be achieved before an invention becomes an innovation (Mokyr 1990, pp. 248 ff.) It makes a difference, however, whether the patent protects a product or a process. In dyestuffs, the American patent law protected the product whereas in Germany it was the process. This protection is advanced as incentive for other chemical firms in Germany to try and find out alternative processes of producing the same product. Even if they failed they gained experience through which they often found a new product. In any case it is not clear whether patent laws pushed technological progress or hampered it.

Agricultural Production

Agriculture was a strategic sector to achieve modern economic growth. Table 3 presents sectoral employment shares for a selected number of countries for benchmark years between 1870 and 1992. The trend is revealed that with generally increasing incomes
the share of people employed in agriculture went down. Fewer and fewer people were needed to produce food for the rest of the ever growing population (on population figures, see Table 1). An adjustment for imports and exports of food does not change this basic statement. Employment shares rose in the other two sectors, industry and services. It should be noticed, however, that the European pattern to some extent differs from other parts of the world: Whereas in Europe industrial employment became the foremost sector before services took the lead, in most countries elsewhere services absorbed the bulk of employees and industry remained the 'second employer' after agriculture had shrunk.
The shrinking of agricultural employment in the course of modern economic growth indicated no decline of the sector, on the contrary, it first of all meant an increasing productivity of the agricultural labour force. (This productivity growth will be explained below.) Secondly, according to the *Law of Engel*[11], with increasing income proportionally less is spent on food. Based on his empirical research Engel had laid down the law, which - more technically formulated - means that the income elasticity of demand for food is below one. Thirdly, tariff protection of indigenous agriculture hampered the shift of the work force towards industry or services. As these three factors did not occur in every country at the same time shifting sectoral shares of employment differed over time and among countries.

Agrarian reforms are often regarded as a precondition of improvements in agriculture. It is very difficult to assess as to which extent institutional reforms paved the way for a higher agricultural productivity, though. According to the approach of the new institutional economics a new arrangement of property rights, which brings the private rate of return closer to the social rate of return, strengthens the incentive to improve on productivity (North/Thomas 1973). In this line of reasoning the feudal heritage from medieval times would have proved an obstacle to technical progress in agriculture. Roughly sketched a feudal system means that people are placed within a hierarchy by birth. They are tied to their position through unequal rights and duties. Land is the most important preindustrial factor of production and land is decisive, as certain properties rights concerning the use of land define the personal position. Abolishing the feudal heritage meant a change in land tenure.

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[11] The German statistician Ernst Engel (1821-1896) was head of the statistical offices of Saxony and Prussia.

Table 3 *Sectoral Employment Shares in Agriculture, Industry and Services (percentage of total employment) 1870, 1913, 1950, 1992*

	USA	France	Germany	UK	Japan	China	Russia
				Agriculture, Forestry, Fisheries			
1870	50	49	50	23	70		
1913	28	41	35	12	60		70
1950	13	28	22	5	48	77	46
1992	3	5	3	2	6	59	17
				Mining, Manufacturing, Construction & Utilities			
1870	24	28	29	42			
1913	30	32	41	44	18		
1950	34	35	43	45	23	7	29
1992	23	28	38	26	35	22	36
				Services			
1870	26	23	22	35			
1913	43	27	24	44	22		
1950	54	37	35	50	29	16	25
1992	74	67	59	72	59	20	47

Sources: See Maddison 1995, p. 39.

In Britain, the enclosure movement put an end to the common use of large parts of the land and moreover to the open field system. Big compact farms emerged with clearly defined property rights of the landed proprietors and their tenant farmers. In France, the French Revolution just expropriated the landed aristocracy and the church. The peasants became the proprietors of their rather small farms. Whereas in Prussia, the reforms after 1807 strengthened the large estates of the landlords, the 'Junkers'. In order to get rid of their obligations flowing from serfdom the peasants had to cede land (or to make huge payments) to their former feudal masters (Cameron 1989, pp. 302 f., for more details and examples). As to the United States one should not forget that until the American Civil War (1861-1865) agriculture in the south was largely organised as slave plantation system. The slave population had originally been captured in black Africa. With the victory of the young industrial capitalism of the north and middle west these slaves were freed. The economic viability of the slave economy was a focus of the *New Economic History* approach[12] in the United States. In the beginning the findings raised some controversy but now it is accepted that the slave plantation system was a profitable enterprise and not obsolete in 'economic' terms (Fogel/Engerman 1974).

At the beginning of the 19th century, Britain boasted of the most productive agriculture in

[12] In this approach rising in the 1960s standard economic theory and econometrics are applied in historical research. Some call it hence 'Cliometrics'.

Europe as she had introduced the system of convertible husbandry rather early. This was an alternative to the traditional rotation pattern of arable followed by fallow in that pasture was integrated. The grazing of animals such as cattle or horses reduced fallow and restored the fertility of the soil at the same time. Even after the 1840s, when the Corn Laws were repealed (thereby abolishing any protection of British agriculture) both British agriculture and British industry reached their peaks in performance as compared to other nations. Technical improvements such as light iron ploughs, steam threshers, mechanical harvesters and commercial fertilizers increased the productivity. In contrast to Germany and France, Britain did not reintroduce protective tariffs, when cheap American grain reached her markets. Like Denmark and the Netherlands, she stuck to free trade and during the second half of the 19th century her agriculture switched more and more to higher value products such as high quality meat and dairy products. Frequently, imported grain was used as feed. Not only Britain but soon most of the industrialising economies constantly raised their agricultural productivity. The highest levels of labour productivity, however, were reached in 'free born' nations such as North America, Argentina, Australia and New Zealand. Abundant in land and not hampered by any feudal heritage they developed a highly commercialised agriculture, which applied technical improvements very efficiently. Marketed for exports, however, they brought about radical changes in West-European agriculture. With the drastic reduction of overseas transport costs cereal from overseas penetrated European markets, which in the 1860s were not protected any more. Around 1880, the two most important continental powers, namely Germany and France, resumed to protecting their agriculture. This resort to protectionism partly explains why in 1913 the share of agricultural employment in Germany and France was that much higher than in free trade Britain. As France and Germany were of the core countries of the European Community from 1958 onwards its agricultural policy clearly bears the impress of their historical heritage of the 19th century.

Economic Ties among Countries and Regions of the World

During the 19th century, international trade increased much faster than production. Between 1800 and 1913, the worldwide production per capita grew a bit more than 7 per cent per decade whereas foreign trade increased its volume by about 33 per cent per decade. These rough estimates reflect the hitherto unknown speed in which the economic ties among nations and regions of the world integrated (Bairoch 1973). The enormous increase of world trade cannot be ascribed to the exchange between Europe and overseas countries, but it rather resulted from an intensified trade among the most advanced nations within Europe. And even in the regions outside of Europe the exchange between Europe and the European overseas settlements dominated. In 1913, still two thirds of world trade volume were concentrated on Europe[13] with

[13] See the table in Rostow 1978, pp. 70 ff. Rostow relies directly or indirectly on estimates by contemporaries done around 1900 (Mulhall, Neumann-Spallart). The data probably do not capture foreign trade in South-East Asia adequately.

Britain alone comprising about one quarter of world trade for a long time and in 1913 she still absorbed 16 per cent. Germany and France were the other large trading nations with 12 and 7 per cent in 1913. The European dominance did not ease off until 1913 although the share of North-America had augmented by then (14% in 1913). Subsequently in particular Britain lost grounds.

The growth of international trade was made possible mainly by drastically reduced transaction costs. First of all the transportation costs for passengers and goods decreased vastly, especially so in the second half of the 19th century. Harley (1989) compiled freight rates of coal shipment for a period including the decisive transition from the wooden sailing vessel to the iron steamer. Prior to the 1860s, he registers no falling trend in the overall level of freight rates. But thereafter the rates declined dramatically until the early 1890s, and in subsequent years they fell rather moderately. Before 1914, on shipments between British and continental ports the rates dropped to 40 per cent of the level of the 1850s, and on long distances (to South America) they went down to one third. Brentano (1911) analysed the influence of declining freight rates from America on the price of wheat in London. (All prices refer to one quarter of wheat): In 1868, freight from Chicago to New York made up about 7 shilling for shipments on water and railway combined and about 10 shilling by train only. The freight on steamboats to Liverpool made up 4.6 shilling. In 1902, the corresponding rates were about 2.3 and 1 shilling. The price of wheat in Britain declined from 64 to 28 shilling between 1868 and 1902. On the European continent, freight rates for railway and inland navigation likewise dropped drastically during the second half of the 19th century.

The decline of transportation costs undermined the free trade movement in Europe, though. This movement was part of a general adoption of liberal ideas. During the 1850s and 1860s, a lot of European countries abolished restrictions on founding enterprises, making even joint-stock companies possible without any charter. The construction of railways was deregulated and left to the working of the free market. Concerning customs policy Britain had moved to free trade during the 1840s. In their strong commitment to liberalism leading politicians and elite groups tried to translate their ideas into practice by creating a free trading zone in Western and Central Europe. In 1860, France and Britain concluded the Cobden-Chevalier Treaty, which planned to abolish all import duties. As it incorporated a most-favoured-nation-clause the free-trading zone bilaterally agreed upon could easily be extended multilaterally. Belgium joined the treaty in 1861, Prussia followed in 1862, Italy in 1863, Switzerland in 1864, Sweden, Norway, Spain and the Netherlands in 1865. But the unexpectedly high export of overseas cereals to Europe in combination with the long term economic slump (the first Great Depression) from the 1870s onward shook the liberal system. Namely Germany and France resorted to the reintroduction of protective tariffs. They could not forfeit the reduction in transportation costs, though. So the long established ties among a lot of economies were not broken. Communications were further facilitated by innovations such as telephone and telegraph and the emergence of the gold standard under British leadership bestowed a stable currency system on the core countries of the industrialising world. In short, the late 19th century witnessed a unique freedom for people, commodities and capital to move about from one country to another.

Conclusions on Industrialisation

In the long run industrialisation raised the living standards of those countries industrialised in the first round enormously. This meant higher income levels, improved education and no less than a longer life expectancy. Hence a worldwide industrialisation suggests itself as the solution to worldwide (economic) problems. But from the experience of the first industrialisation that was realised through an ever intenser exploitation of fossil energy sceptical contemporaries warn us against a further extension and transfer of industrialisation, which seems no option for the future. As against that others trust in scientific and technological progress to be capable of coping with sequels as the greenhouse effect. Maybe a recourse to the use of preindustrial energy resources (sun, wind, water) proves a viable resort without risking any loss of welfare for mankind.

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